IOAG Lunar Communications Architecture StudyI

OAG Lunar Communications Architecture Working Group

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IOAG Lunar Communications Architecture Study
Purpose & Work Items

- Identify key issues concerning interoperability and cross support among the missions/network assets operated by the IOAG member agencies.
- Generated a recommendation for the down-selected frequency, modulation, ranging, and coding for the future lunar architecture for input to the Lunar Orbital Platform – Gateway (LOP-G), formerly Deep Space Gateway (DSG), Project.

  [So far, there exists strong consistency between the DSG requirements for communication standards and the IOAG lunar communications architecture "requirements" in the following areas:
  - Frequency, Modulation, Coding and Sync, Ranging
  - Space Data Link Layer Protocols
  - Network Layer Protocols (DTN, LTP, etc.)]
- Define relay service(s). Define all service types. Define Lunar-Earth Space Internet.
- Define Lunar Relay Network.
  - Determine the need for dedicated relay orbiter(s). Understand the use cases. If yes,
    - Determine the optimal orbits.
    - Perform coverage analysis.
    - Perform link analysis.
  - Identify the opportunistic relay orbiter(s).
    - Perform opportunistic coverage analysis.
    - Perform opportunistic link analysis

Purpose of the Study

To define the future Lunar Communications Architecture that will facilitate potential cross support to Lunar missions by communication assets owned and/or operated by the IOAG member agencies and their affiliated companies in the private sectors.

Potential Lunar Missions to be Launched During 2018-2028 Decade

Private Sector Endeavors:
- Moon Express
- Astrobotic
- Blue Origin
- etc.

are not listed here due to uncertain launch date and lack of involvement of IOAG agencies.

Mission	Launch Year	Agency	# of Vehicles	Mission Type
Chandrayaan-2	2019	ISRO	3	Orbiter/lander/rover
Chang'e 4	2018	CNSA	3	Farside Lander/rover + Relay Orbiter
Chang'e 5	2019	CNSA	2	Orbiter/rover for sample return
Chang'e 6	2020	CNSA	2	Orbiter/rover for sample return
Korea Pathfinder Lunar Orbiter (KPLO)	2020	KARI	1	Orbiter
Korean Lunar Mission Phase 2	2020s	KARI	3	Orbiter/lander/rover
Luna-Glob	2019	Roscosmos	1	Lander
Luna Resurs-1 Orbiter	2022	Roscosmos	1	Orbiter
Luna Resurs-1 Lander	2023	Roscosmos	1	Lander
Luna-Grunt (Luna 28) Resurs-1	2020s	Roscosmos	1	Capsule
Smart Lander for Investigating Moon (SLIM)	2021	JAXA	1	Lander
Lunar Surface Science missions*	2020s	NASA	TBD	Lander/rover
Lunar Communications Pathfinder*	2020s	Goonhilly, SSTL, UK Space, ESA	1	Relay Orbiter
Lunar Orbital Platform-Gateway (LOP-G)	2022, 2024, 2025, 2026	NASA	4	Orbiter in Near-Rectilinar Halo Orbit
International Lunar Exploration Precursor mission*	2024	ESA	3	Lander + Rover + Ascender to and from cislunar transit habitat
International Human Lunar Surface Architecture*	2028 (pre-positioned assets 2027)	ESA	3	Lander + Rover + Ascender to and from cislunar transit habitat
Exploration Mission-1 (EM-1)**	2020	NASA	1	Orbiter
Exploration Mission-2 (EM-2)**	2022	NASA	1	Orbiter
Lunar Flashlight	2020	NASA	1	CubeSat Orbiter
Lunar IceCube	2020	NASA	1	CubeSat Orbiter
Lunar H-Map	2020	NASA	1	CubeSat Orbiter
ArgoMoon	2020	ASI	1	CubeSat Orbiter
Omotenashi	2020	JAXA	1	CubeSat Lander
Equuleus	2020	JAXA	1	CubeSat Orbiter
SpaceIL	2020	Israel non-profit	1	Small Lander

Down-Selection of Frequency, Modulation, Ranging, Coding, and Space Data Link Protocols
- Purpose -

Driven by the need for interoperability among future Lunar missions, including NASA's Lunar Orbital Platform – Gateway (LOP-G) and Lunar surface science missions, it's been recognized that the set of CCSDS standards are key to the design of NASA's Lunar space communications architecture. Given the rich repertoire of the standards produced by the CCSDS, it is imperative for us to pick and choose the suitable standards as the solutions to the problems.

- The recent effort started in late November 2018. It resulted in a white paper delivered to the Deep Space Gateway (now the LOP-G) system team.
- Input has been incorporated into the requirement document "International Communication System Interoperability Standards (ICSIS)".
- ~ 40 CCSDS standards have been accepted by the LOP-G and, possibly other NASA's Lunar missions.

Factors Taken into Account for the Selection of CCSDS Standards

- Interoperability between the lunar vehicles (orbiters, landers, rovers) and their supporting network assets (owned by NASA, international partners, and commercial providers).
- Interoperability between a lunar relay orbiter and its user vehicles.
- Costs of implementation
- Constraints due to spectral limitation: ITU, SFCG and NTIA imposed

Selection of Frequency Bands

Source/Destination	Frequency Bands[1]
Earth to Moon (Lunar orbiter or surface vehicles)	RF – low rate: X-band 7190-7235 MHz
	RF – high rate: 22 GHz Ka-band 22.55-23.15 GHz
	Optical: 1064 nm[4]
Moon (Lunar orbiter or surface vehicles) to Earth	RF – low rate: X-band 8450-8500 MHz
	RF – high-rate: 26 GHz Ka-band 25.5-27.0 GHz
	Optical: 1550 nm[4]
Cross-Link (lunar relay orbiter-other relay orbiters)	22.55-23.55 GHz 25.6-27.225 GHz
	Optical: 1550 nm[4]
Proximity-Link (lunar relay orbiter to lunar surface or user orbiter)	RF – low rate: S-band 2025-2110 MHz
	RF- high rate: 22 GHz Ka-band 22.55-23.15 GHz
	Optical: 1550 nm[4]
Proximity-Link (lunar surface or user orbiter to lunar relay orbiter)	RF – low rate: 2200-2290 MHz
	RF- high rate: 26 GHz Ka-band 25.5-27 GHz
	Optical: 1550 nm[4]

- Frequency bands for the various Lunar communication links are in full compliance with the SFCG allocations.
- Earth-to/from-Moon links:
  - Selected X-band for low-rate links, i.e., the engineering TT&C links.
  - This is a significant departure from the S-band commonly used by the past Lunar missions.
- High-rate data links:
  - Selected 22 GHz Ka-band for all RF high-rate forward data links, regardless of Earth-to-Moon, crosslink, or proximity links.
  - Selected 26 GHz Ka-band for all RF high-rate return data links, regardless of Earth-from-Moon, crosslink, or proximity links.
  - Selected CCSDS high-photon efficiency (HPE) standard for all optical links regardless of Earth-Moon, crosslink, or proximity links.
- Lunar surface-to-surface Links: May be subject to negotiation with commercial wifi service providers

Lunar Surface to Lunar Surface	2400-2480 GHz

Selection of Frequency Bands

- High-rate RF links: 37-38 GHz and 40-41 GHz bands for Lunar Orbiter-to-Earth and Earth-to-Lunar Orbiter, respectively, as the alternative to the 26 GHz and 22 GHz bands for high-rate links:
  - Argument for 37-38 GHz and 40-41 GHz bands:
    - RFI-free in the long term, increased operability.
    - Both bands would allow “seamless” transition of human exploration vehicles from the Earth to Moon to Mars.
  - Argument against:
    - High implementation costs for adding this capability to the DSN and the RF terminal on-board the Lunar Orbiter.
    - RFI with proximity high-rate links and other missions could be avoided and mitigated through coordinated allocations. Since the maximum data rate for the Moon-to-Earth link is ~100 - 300 Mbps (as projected), given the 1.5 GHz total bandwidth this may not be a serious problem.
    - If the 22 GHz/26 GHz bands indeed become congested or interference prone, it is about time for some high-rate missions to move to optical. As an example, the LOP-G will have optical communications capability for its Lunar proximity and Moon-Earth links anyway.
- High-rate optical links: CCSDS High Data Rate (HDR) or Optical On-Off Keying (O3K) vs. High Photon Efficiency (HPE) standard.
  - Our selection on the HPE for <u>all</u> optical links is primarily for avoiding any extra implementation cost due to multiple approaches. The solution based on the HPE blue book standard meets the data rate requirements for all lunar links, i.e., the proximity links, cross links, and Earth-Moon links.

Source/Destination	Frequency Bands[1]	Modulation[2]
Earth to Moon (Lunar orbiter or surface vehicles)	RF – low rate: X-7190-7235 MHz	Nominal: GMSK with PN
		Spacecraft contingency: PCM/PSK/PM, on subcarrier
	RF – high rate: Ka-22.55-23.15 GHz	Filtered OQPSK, suppressed carrier
	Optical: 1064 nm[4]	PPM[4]
Moon (Lunar orbiter or surface vehicles) to Earth	RF – low rate: X-8450-8500 MHz	Nominal: GMSK with PN
		Spacecraft contingency: PCM/PSK/PM, on subcarrier
	RF – high-rate: Ka-25.5-27.0 GHz	Filtered OQPSK, suppressed carrier
	Optical: 1550 nm[4]	PPM[4]
Cross-Link (lunar relay orbiter-other relay orbiters)	22.55-23.55 GHz 25.6-27.225 GHz	Filtered OQPSK, suppressed carrier
	Optical: 1550 nm[4]	PPM[4]
Proximity-Link (lunar relay orbiter to lunar surface or user orbiter)	RF – low rate: S-2025-2110 MHz	Option 1 - PCM/PM/NRZ, Residual carrier (for FDMA); Option 2 - CDMA
	RF- high rate: Ka-22.55-23.15 GHz	Filtered OQPSK, suppressed carrier
	Optical: 1550 nm[4]	PPM[4]
Proximity-Link (lunar surface or user orbiter to lunar relay orbiter)	RF – low rate: S-2200-2290 MHz	Option 1 - PCM/PM/NRZ, Residual carrier (for FDMA); Option 2 - CDMA
	RF- high rate: Ka-25.5-27 GHz	Filtered OQPSK, suppressed carrier
	Optical: 1550 nm[4]	PPM[4]

Selection of Modulation Schemes

Down-selected the available CCSDS modulation schemes for use by NASA's future lunar missions:

- Independence on link directionality.
- Single modulation for all RF high-rate links regardless of Earth-Moon, crosslink, or proximity links.
  - Filtered OQPSK
- Single modulation for all optical links regardless of Earth-Moon, crosslink, or proximity links.
  - Pulse Position Modulation (PPM)
- Still had to settle with multiple modulations due to:
  - The need for different carrier types: suppressed carrier, residual carrier, and subcarrier.
  - The drive for bandwidth efficiency: in the case of X-band with only 45 MHz of spectrum available in total for Category A space missions.
  - Critical dependency on the modulation defined for the IOAG Spacecraft Emergency Cross Support (SECS) service.

Source/Destination	Frequency Bands[1]	Modulation[2]	Ranging
Earth to Moon (Lunar orbiter or surface vehicles)	RF – low rate: X- 7190-7235 MHz	Nominal: GMSK with PN	**Simultaneous PN ranging and data**
		Spacecraft contingency: PCM/PSK/PM, on subcarrier	
	RF – high rate: Ka- 22.55-23.15 GHz	Filtered OQPSK, suppressed carrier	None
	Optical: 1064 nm[4]	PPM[4]	None
Moon (Lunar orbiter or surface vehicles) to Earth	RF – low rate: X- 8450-8500 MHz	Nominal: GMSK with PN	**Simultaneous PN ranging and data**
		Spacecraft contingency: PCM/PSK/PM, on subcarrier	
	RF – high-rate: Ka- 25.5-27.0 GHz	Filtered OQPSK, suppressed carrier	None
	Optical: 1550 nm[4]	PPM[4]	None
Cross-Link (lunar relay orbiter-other relay orbiters)	22.55-23.55 GHz 25.6-27.225 GHz	Filtered OQPSK, suppressed carrier	None
	Optical: 1550 nm[4]	PPM[4]	None
Proximity-Link (lunar relay orbiter to lunar surface or user orbiter)	RF – low rate: S- 2025-2110 MHz	Option 1 - PCM/PM/NRZ Residual carrier (for FDMA);	**Simultaneous PN and data**
		Option 2 - CDMA[20]	**PN ranging**
	RF- high rate: S- 22.55-23.15 GHz	Filtered OQPSK, suppressed carrier	None
	Optical: 1550 nm[4]	PPM[4]	None
Proximity-Link (lunar surface or user orbiter to lunar relay orbiter)	RF – low rate: S- 2200-2290 MHz	Option 1 - PCM/PM/NRZ Residual carrier (for FDMA);	**Simultaneous PN and data**
		Option 2 - CDMA[20]	None
	RF- high rate: Ka- 25.5-27 GHz	Filtered OQPSK, suppressed carrier	**PN ranging**
	Optical: 1550 nm[4]	PPM[4]	None

Selection of Ranging Approach

- Down-selected available CCSDS ranging approaches:
  - Only PN ranging is selected.
- GMSK modulation for Earth-Moon link:
  - The GMSK modulation enables the efficient use of the spectrally limited X-band, both uplink and downlink. However, conventional GMSK method operates on suppressed carrier which precludes modulation of ranging signal.
  - The CCSDS RF and Mod blue book (2017 version) specifies a new method of using GMSK modulation for simultaneous transmission of telemetry and PN ranging. However, there is no technical reason why this approach cannot be applied for simultaneous transmission of forward data and PN ranging over the Earth-to-Moon link. Again, this is a case of independence on link directionality.

Selection of Coding Schemes

Source/Destination	Frequency Bands[1]	Coding[3]
Earth to Moon (Lunar orbiter or surface vehicles)	RF – low rate: X- 7190-7235 MHz	Nominal: LDPC[8,3], coding rates – 1/2, 2/3, 4/5, 7/8 Spacecraft contingency: Option 1 - BCH[12] Option 2 – LDPC[8,3], coding rates – 1/2
	RF – high rate: Ka- 22.55-23.15 GHz	LDPC[8,3], coding rates – 1/2, 2/3, 4/5, 7/8
	Optical: 1064 nm[4]	LDPC[5] (TBD)
Moon (Lunar orbiter or surface vehicles) to Earth	RF – low rate: X- 8450-8500 MHz	Nominal: LDPC[8,3], coding rates – 1/2, 2/3, 4/5, 7/8 Spacecraft contingency: Option 1 - BCH[12] Option 2 – LDPC[8,3], coding rates – 1/2
	RF – high-rate: Ka- 25.5-27.0 GHz	LDPC[8,3], coding rates – 1/2, 2/3, 4/5, 7/8
	Optical: 1550 nm[4]	SCPPM[5]
Cross-Link (lunar relay orbiter-other relay orbiters)	22.55-23.55 GHz 25.6-27.225 GHz	LDPC[8,3], coding rates – 1/2, 2/3, 4/5, 7/8
	Optical: 1550 nm[4]	LDPC[5] (TBD)
Proximity-Link (lunar relay orbiter to lunar surface or user orbiter)	RF – low rate: S- 2025-2110 MHz	LDPC[8,3], coding rates – 1/2, 2/3, 4/5, 7/8
	RF- high rate: Ka- 22.55-23.15 GHz	LDPC[8,3], coding rates – 1/2, 2/3, 4/5, 7/8
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Proximity-Link (lunar surface or user orbiter to lunar relay orbiter)	RF – low rate: S- 2200-2290 MHz	LDPC[8,3], coding rates – 1/2, 2/3, 4/5, 7/8
	RF- high rate: Ka- 25.5-27 GHz	LDPC[8,3], coding rates – 1/2, 2/3, 4/5, 7/8
	Optical: 1550 nm[4]	SCPPM[5]

Down-selected available CCSDS coding schemes:

- LDPC code family (all coding rates) is selected for all links, regardless of Earth-to-Moon, crosslink, or proximity links.
- The only potential exception is the RF low-rate link for spacecraft contingency/ emergency. Must be in compliance with the coding defined for the IOAG Spacecraft Emergency Cross Support (SECS) service, likely the BCH code.
- LDPC code offers a significant performance advantage over the Reed-Solomon/convolutional concatenated code: ~2.5 dB for rate ½ code.

Forward error correction (FEC) code for Earth-to-Moon link:

- It has long been asserted by some that all FEC codes, including the high-performance code like LDPC code, defined in the CCSDS TM Synchronization and Channel Coding blue book are only applicable to spacecraft-to-Earth links.
- In view of the symmetric property of the AOS/USLP space data link protocol, since the CCSDS LDPC code can be applied to the AOS/USLP frames over Lunar Orbiter-to-Earth link, we have decided to use it for the AOS/USLP frames over Earth-to-Lunar Orbiter link, crosslink, and proximity link.

Source/Destination	Frequency Bands[1]	Space Data Link Protocol
Earth to Moon (Lunar orbiter or surface vehicles)	RF – low rate: X- 7190-7235 MHz	Nominal: AOS[6], USLP[7]
		Spacecraft contingency: AOS[6], USLP[7]
	RF – high rate: Ka- 22.55-23.15 GHz	AOS[6], USLP[7]
	Optical: 1064 nm[4]	AOS[6], USLP[7]
Moon (Lunar orbiter or surface vehicles) to Earth	RF – low rate: X- 8450-8500 MHz	Nominal: AOS[6], USLP[7]
		Spacecraft contingency: AOS[6], USLP[7]
	RF – high-rate: Ka- 25.5-27.0 GHz	AOS[6], USLP[7]
	Optical: 1550 nm[4]	AOS[6], USLP[7]
Cross-Link (lunar relay orbiter-other relay orbiters)	22.55-23.55 GHz 25.6-27.225 GHz	AOS[6], USLP[7]
	Optical: 1550 nm[4]	AOS[6], USLP[7]
Proximity-Link (lunar relay orbiter to lunar surface or user orbiter)	RF – low rate: S- 2025-2110 MHz	AOS[6], USLP[7]
	RF- high rate: Ka- 22.55-23.15 GHz	AOS[6], USLP[7]
	Optical: 1550 nm[4]	AOS[6], USLP[7]
Proximity-Link (lunar surface or user orbiter to lunar relay orbiter)	RF – low rate: S- 2200-2290 MHz	AOS[6], USLP[7]
	RF- high rate: Ka- 25.5-27 GHz	AOS[6], USLP[7]
	Optical: 1550 nm[4]	AOS[6], USLP[7]

Selection of Space Data Link Protocol

Down-selected the available CCSDS space data link protocols for use by NASA's future lunar missions:

- Independence on link directionality.
- A single space data link protocol for all links, regardless of Earth-Moon, crosslink, or proximity links.
- Driven by high-rate links, USLP is selected as the single space data link protocol. In the interim, before the USLP blue book becomes available, the AOS protocol is the placeholder.

AOS/USLP vs. Proximity-1 protocol for Lunar proximity links and crosslink:

- The Proximity-1 protocol as it is in the blue book now will require fundamental modifications to make it suitable for the high-rate proximity links, e.g., the go-back-N retransmission and the field for frame sequence number (being limited to only one octet unlike 3 octets in AOS).
- The USLP (and AOS) protocol is symmetric in nature. It has the right property needed for all types of Lunar proximity links and crosslinks.
- Unlike the TM and TC protocols, the AOS (and USLP) was designed for high-rate links. It can be readily adopted for purpose of Lunar proximity link and crosslinks, regardless of RF or optical.
- For supporting multiple user vehicles concurrently, the USLP will preserve and take advantage of the hailing capability and control mechanism of the Proximity-1 protocol.

CCSDS/SFCG Specifications

1. SFCG 32-2R1 Communication Frequency Allocations and Sharing in the Lunar Region.
2. CCSDS 401.0-B-27 Radio Frequency and Modulation Systems--Part 1: Earth Stations and Spacecraft. Blue Book. Issue 27. November 2017.
3. CCSDS 131.0-B-3 TM Synchronization and Channel Coding. Blue Book. Issue 3. September 2017.
4. CCSDS 141.0-R-1 Optical Communications Physical Layer, Red Book November 2017, currently undergoing publication.
5. CCSDS (Reference TBD) Optical Communications Coding & Synchronization – publication date TBD.
6. CCSDS 732.0-B-3 AOS Space Data Link Protocol. Blue Book. Issue 3. September 2015.
7. CCSDS 732.1-R-3.1 Unified Space Data Link Protocol. Red Book. November 2017, currently undergoing publication.
8. CCSDS (TBD Reference) Coding & Synchronization Sub-layer High Rate Uplink Protocol for AOS & USLP.
9. CCSDS 414.1-B-2 Pseudo-Noise (PN) Ranging Systems. Blue Book. Issue 2. February 2014.
10. CCSDS 415.1-B-1 Data Transmission and PN Ranging for 2 GHz CDMA Link via Data Relay Satellite. Blue Book. Issue 1. February 2011.
11. CCSDS 355.0-B-1 Space Data Link Security Protocol. Blue Book. Issue 1. September 2015.
12. CCSDS 231.0-B-3 TC Synchronization and Channel Coding. Blue Book. Issue 3. September 2017.
13. IEEE 802 Part 11 Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, IEEE Standard 802.11-2007

CCSDS Standards at Network Layer and Application Layer

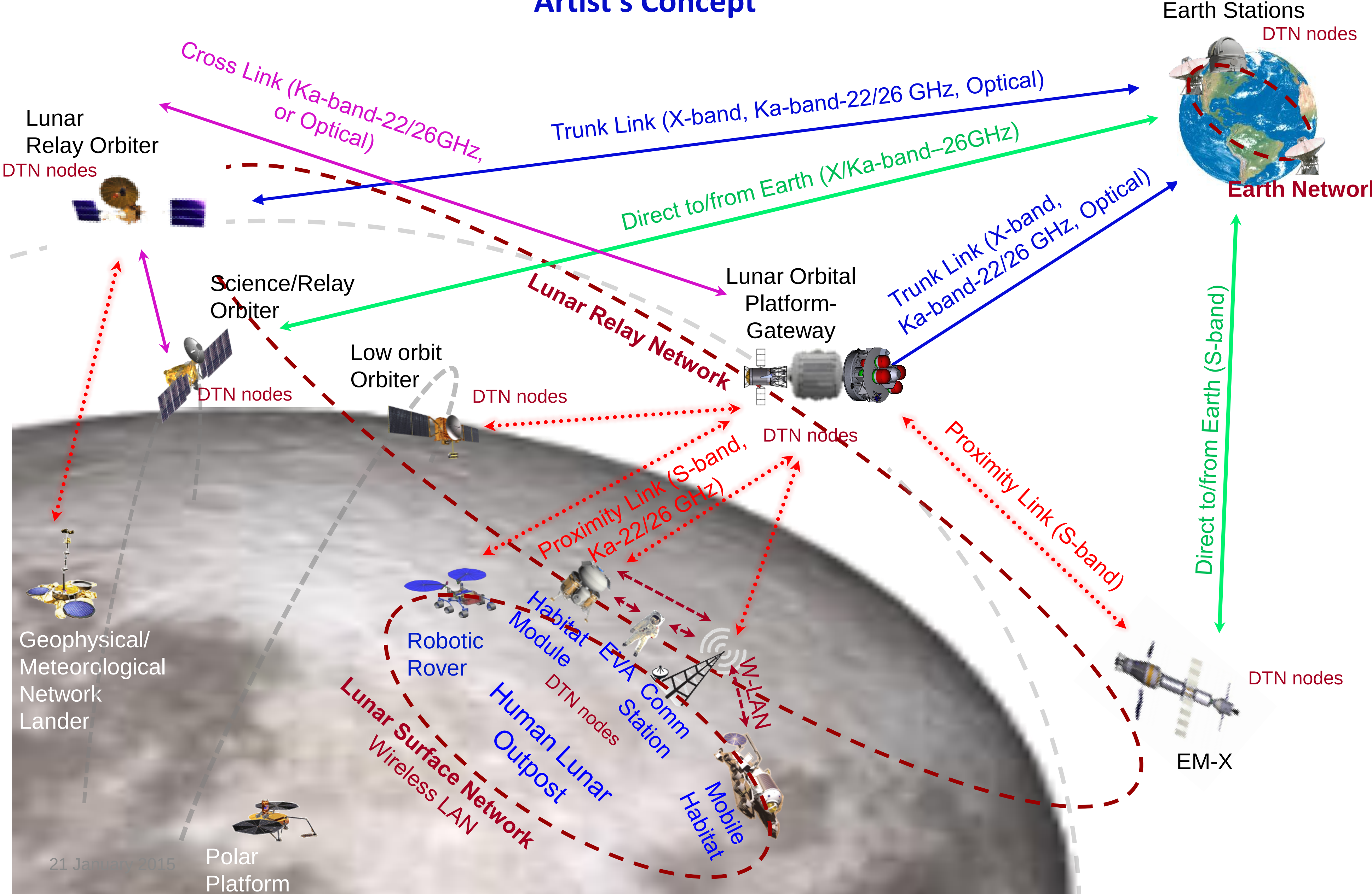
- Disruption/Delay Tolerant Network (DTN): Bundle Protocol (BP) and Licklider Transmission Protocol (LTP)
- Encapsulation Service
- CCSDS File Delivery Protocol (CFDP): Class 1 and Class 2 only
- Asynchronous Messaging Service (AMS)
- Tracking Data Message (TDM)
- Space Link Extension (SLE) – Forward Control Link Transmission Unit (CLTU) service
- Space Link Extension (SLE) – Return All Frame (RAF) service
- Space Link Extension (SLE) - Return Channel Frame (RCF) service
- Cross Support Transfer Service (CSTS) – Monitor Data Service
- Cross Support Transfer Service (CSTS) – Specification Framework
- Space Data Link Security (SDLS)

Lunar Relay Service(s)

- Relay data service:
  - An end-to-end service that offers the transfer of a single interoperable entity over one or more assets, i.e., relay assets, between the two end points. This single interoperable entity must be at, or at a higher level than Layer 3 on the ISO model. This single interoperable entity shall be created at the start point and preserved during its transition through the relay asset(s) until acceptance at the end point.
  - For the lunar communications architecture this data entity is a bundle packet.
- In addition to the relay data services, the involved relay asset(s) may provide other types of services, e.g., network time service, in-situ tracking service, and in-situ navigation service.
- The relay services are end-to-end services involving:
  - Multiple physical links: Proximity link, Direct-To-Earth links, Direct-From-Earth link
  - Interfaces at multiple layers: Physical, data link, and network layers
- The exhibition of network layer service and multiple links across two planetary bodies, Moon and Earth points to the need for defining a Interplanetary Space Internet.

Lunar Planetary Network as an Interplanetary Space Internet
(Lunar Relay Network + Lunar Surface Network + Earth Network)

Artist's Concept



Lunar Relay Services
Types of Services

Service Type	Description
Space Internetworking Service	Provides routed, assured, secure delivery of mission data using DTN protocol suite
Network Time Service	Provides network-wide time knowledge using a Network Time Protocol (NTP)
In-situ Tracking Service	**Ranging:** Measures the time delay between the user vehicle and the relay orbiter using RF or optical transmission (convertible to distance)
	Doppler: Measures and time tags the phase of the transmitted forward carrier and/or the received return carrier at the relay orbiter
	Antenna Pointing Angle: Measures the pointing angle of the relay RF antenna or optical terminal as it tracks the user vehicle
In-situ Navigation Service	**Positioning:** Determines the location of the user vehicle, on Lunar surface or in Lunar orbit, based on available tracking data types
Application Layer Services enabled by relay services are:	
End-to-end file service	Transfers files bi-directionally between a user vehicle and ground system or between two user vehicles
End-to-end messaging service	Transfers messages bi-directionally between a user vehicle and ground system or between two user vehicles
End-to-end space packet service	Transfers CCSDS space packets from a user vehicle to ground system or between two user vehicles

Lunar Relay Services

- Relay methods could be bent-pipe and store-and-forward.
- The store-and-forward method is proposed for Lunar relay network given the following assessment:

Relay method	Pros	Cons
Bent-pipe (regenerative)	1. Simplicity in relay mechanism. The relay asset is essentially a physical layer entity, like a piece of wire. 2. Minimum on-board processing is to take place. Latency is low. 3. Minimum demands on additional on-board resources, e.g., memory and data store.	1. Fragility in service provision, as the relay asset must maintain a guaranteed visible, direct path with both source and destination throughout the contact period for data transfer. 2. For Lunar relay, there is no equivalent of geosynchronous or geostationary orbits as a stable orbit for user vehicles' view. 3. Difficulty in providing higher level and value-added services to user vehicles. For example, provision of network layer functionality, e.g. dynamic routing, is not feasible.
Store-and-forward	1. Flexibility in service provision, the relay asset does not have to rely on both source and destination being in view throughout the contact period for data transfer. 2. Amenable to the provision of higher level and value-added services to user vehicles. For example, provision of network layer functionality, e.g. dynamic routing, is feasible.	1. Complexity in relay mechanism. The relay asset must provide physical, data link, and network layer capabilities for interfacing with both its source and destination vehicles. 2. Heavy demands on additional on-board resources, e.g., processing power and data store.

Lunar Relay Services
Relay Link Access Modes

- The Lunar relay orbiter will provide both single access and multiple access modes.
- Single access
  - All CCSDS link layers are single access – except Proximity-1 which has the multiple access though frequency channelization.
- Multiple access:
  - *Spatial domain* would require the configuration phased array antennas or optical terminals to accuracy point and discrimination between multiple relay users, i.e., orbiters and landers/rovers. There are many commercially available phased array antennas.
  - *Frequency domain:*
    - This is achieved through channelizing the ITU frequency allocation for the architecture. The could be done by managing the allocation or defining an automatic method for switching frequencies (as defined in CCSDS Proximity-1)
  - *Time domain*
    - Sharing the same frequency by polling the different vehicles in the architecture. This would require the definition of a Time Domain access scheme that currently does not exist in CCSDS.
  - *Code domain*
    - The use of a coding scheme to allow multiple access – similar to the versions that are used in in WiFi and mobile phones.

Tentatively, we suggest that the Lunar relay orbiter provide:

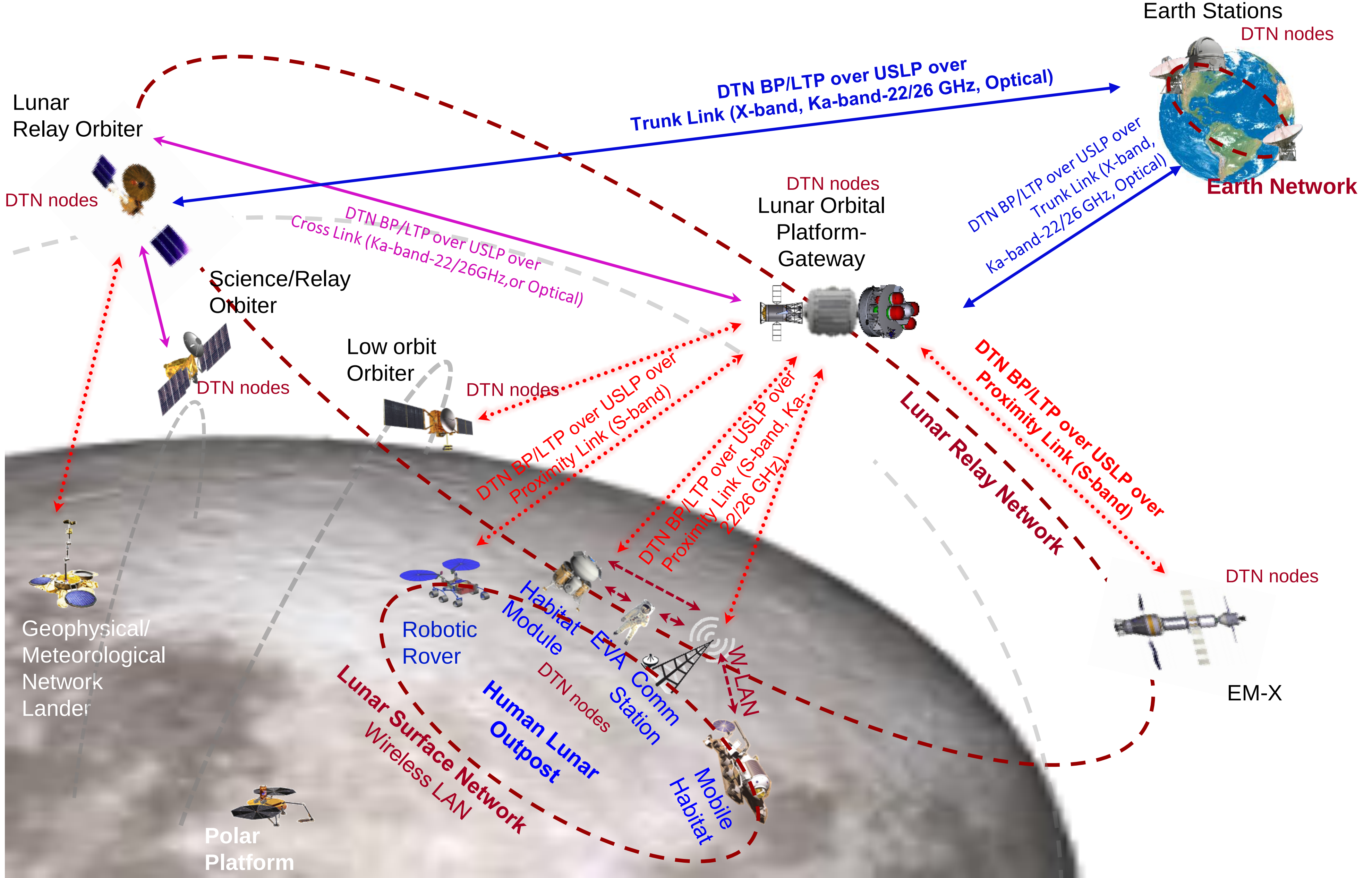
- A proximity single access link, using near-Earth S- and Ka-bands, via a steerable parabolic antenna.
- A proximity multiple access link, using near-Earth S- and Ka-bands to support n (n is TBD) simultaneous users, via a phased array antenna with onboard beamforming.

Lunar Relay Services
Relay Service Initiation Modes

- <u>Pre-scheduled</u>
  - This is currently what is done around Mars and is a operator-in-the loop process. This should be avoided for a Lunar relay services.
- <u>User-initiated Service (UIS*)*</u>
  - The user's request for services is through a service acquisition process carried out by standardized "service user-to-service provider" communications over the Lunar proximity link [Note: In this context, the service provider is the Lunar relay orbiter and the service user is any Lunar vehicle, on surface or in orbit, that is the user of the relay service.]
  - These requests extend beyond requests for proximity link access to requests for instances of relay services as defined in the service type table. That means in the UIS mode the service acquisition process includes:
    - The link acquisition mechanism (or protocol) for access to the proximity link, at link layer: An example of such protocols is the CCSDS Proximity-1 hailing control mechanism used by the USLP.
    - The UIS service acquisition protocol for requesting relay services, at application layer.
  - The service provision, involving service acquisition and service execution, by the Lunar relay orbiter is fully automated, i.e., not pre-scheduled by human operator.

Lunar Relay Network

Artist's Concept



Lunar Relay Orbiters During 2018 - 2028 Period (W. Tai 6/9/2018)

Relay Orbiter	Launch Year	Agency	Earth communication assets	Orbit type	Orbital parameters	Coverage performance	Frequencies & Maximum Data Rates: Earth to Relay	Frequencies & Maximum Data Rates: Relay to Earth	Frequencies & Maximum Data Rates: Relay to Lunar surface or orbital user	Frequencies & Maximum Data Rates: Lunar surface or orbital user to Relay	Space data link protocol	Space network protocol	Relay Services
Lunar Orbital Platform - Gateway (LOP-G)	2022	NASA	DSN, NEN, ESTRACK	Near-Rectilinear Halo Orbit (NRHO)	Orbital period: ~6.25 days. Elliptical polar 4,000 x 70,000 Km adjustable orbit. Max range from S. Pole: 70,000 Km. Max velocity 0.85 Km/s.	Orbital period ~6.25 days. Continuous coverage of S.Pole for 144.6 hours with a gap of 5.4 hours	•X-band: 10 Msps; •Ka-band: at least 10 Mbps (may be 30 Mbps); •Optical: TBD	•X-band: 4 Msps; •Ka-Band: at least 100 Mbps (may be 300 Mbps) •Optical: TBD	•S-band: 10 Msps; •Ka-band: 10 Mbps; •Optical: TBD	•S-band: 4 Msps; •Ka-band: 100 Mbps; •Optical: TBD	•All links: AOS (USLP when CCSDS Blue Book is available)	DTN BP/LTP	Space internetworking service, In-situ tracking service, In-situ navigation service (TBC).
Lunar Communications Pathfinder	2020s	Goonhilly, UK Space	Goonhilly, ESTRACK	Todd Ely Orbit: 12-hour Frozen Orbit	SMA = 6142.4 Km. ECC = 0.59999. INC = 57.7 deg. Perilune = 90 deg. Elliptical polar 500 x 9,900 Km orbit. Max range from S. Pole: ~9,900 Km. Max velocity 0.68 Km/s.	Orbital period 12 hours. Continuous coverage of S.Pole for 9.13 hours with a gap of 2.87 hours.	•X-band: 16 Kbps	•X-band: 3 Mbps	•UHF: 64 Kbps	•UHF: 2 Mbps	•Relay-User links: Proximity-1; •Earth-Relay links: TC/TM	DTN BP/LTP	Space internetworking service
Chang'e-4 Queqiao	2018	CNSA	Kashgar, Jiamusi, Miyun, & Neuquen (Argentina)	Assumption 1: Earth-Moon L2 Lissajous Orbit	74-day Lissajous orbit at Earth-Moon L2 (9 loops). Max range from S. Pole: 90,000 Km.	9 contacts/74 days. Average contact duration at S. Pole is 170 hours. Average Communication gaps at S. Pole is 31 hours.	•S-band: 1 Kbps	•S-band: 2 Mbps	•X-band: 1 Kbps	•X-band: 4x256 Kbps	•Relay-User links: Proximity-1 (TBC); •Earth-Relay links: TC/TM	None (TBC)	Store-&-forward space packet service
				Assumption 2: Earth-Moon L2 Halo Orbit	14-day Halo orbit at Earth-Moon L2. Max range from S. Pole: 84,000 Km.	At S. Pole, 1 contact/14 days with duration of 224 hours, followed by a gap of 102 hours.							
Chandrayaan-2 Orbiter	2019	ISRO	IDSN, DSN	Lunar Circular Orbiter	100 x 100 Km circular orbit. Range from S. Pole: 100 Km.	Orbital period: 2 hours	•S-band: 125 bps	•S-band: 4 Kbps; •X-band: 8.4 Mbps (payload data)	•S-band: 2 Kbps	•S-band: 2 Kbps; •X-band: 256 Kbps (payload data)	•Relay-User links: Proximity-1 (TBC); •Earth-Relay links: TC/TM	None	Store-&-forward space packet service

Lunar Relay Orbiters – Coverage Analysis

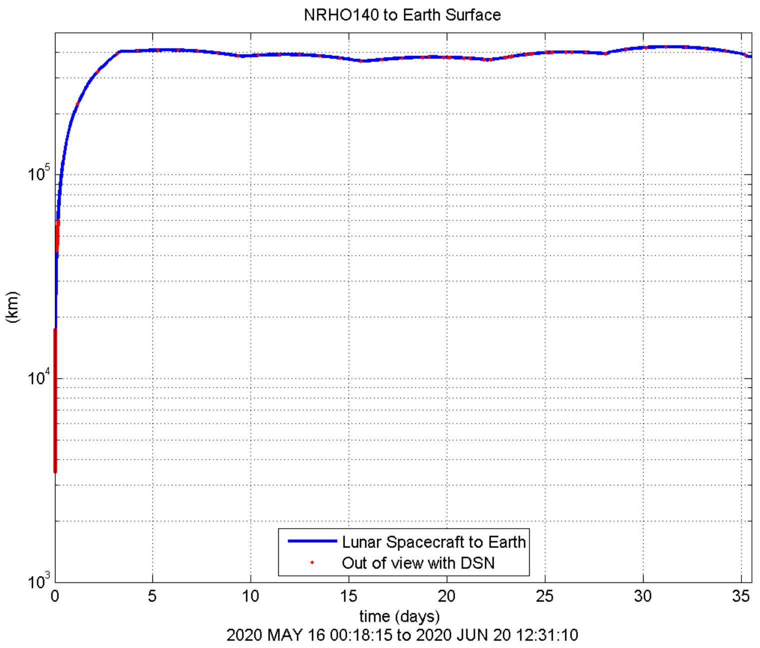
Given the known orbits of the various relay orbiters, perform a coverage analysis:

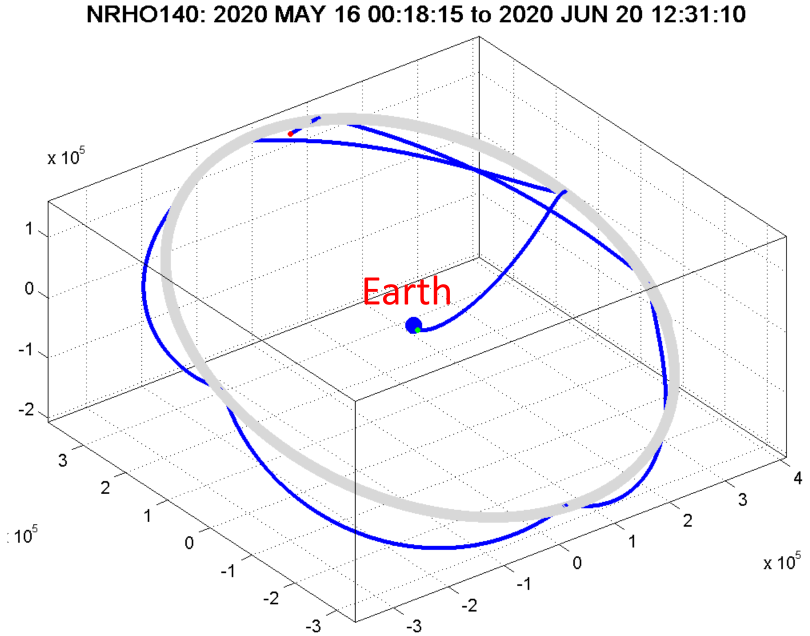
- Lunar Orbital Platform -Gateway (LOP-G)
- Lunar Communications Pathfinder
- Chang'e-4 Queqiao
- Chandrayaan-2 Orbiter: TBD

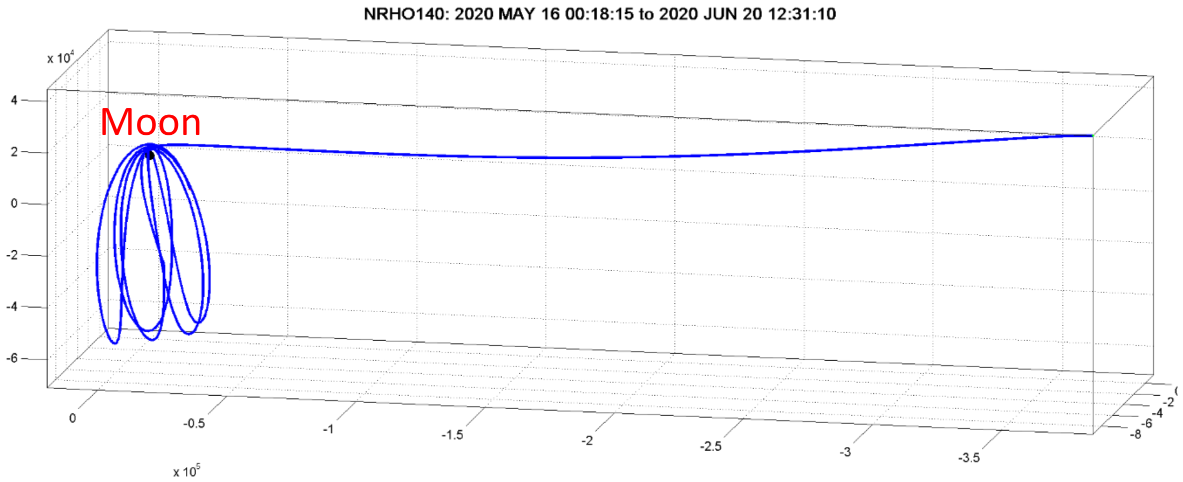
By comparing and correlating these future, near term relay orbiters, draw some lessons, guidance, and recommendations that we could provide to the IOAG member agencies. That includes NASA.

Lunar Orbital Platform – Gateway (LOP-G): NRHO Trajectory

- Orbital period: ~6.25 days.
- Elliptical polar ~4,000 x 70,000 Km, adjustable orbit.
- Max velocity 0.85 Km/s.
- Max range from S. Pole: 70,000 Km.
- Continuous coverage of S. Pole for 144.6 hours with a gap of 5.4 hours



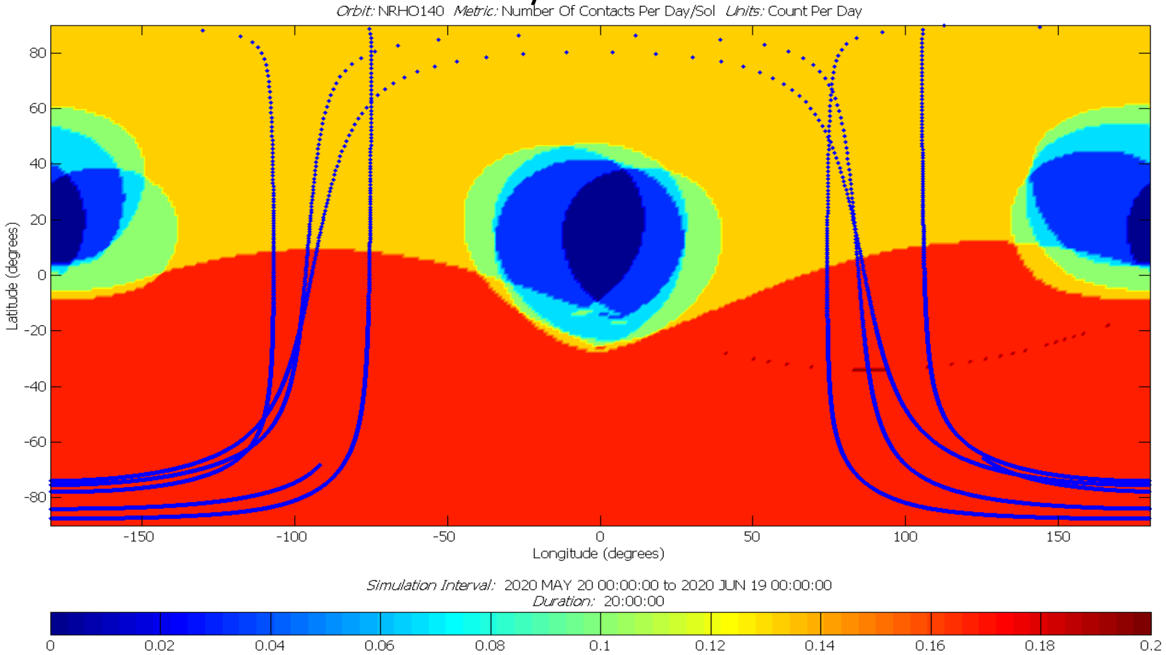




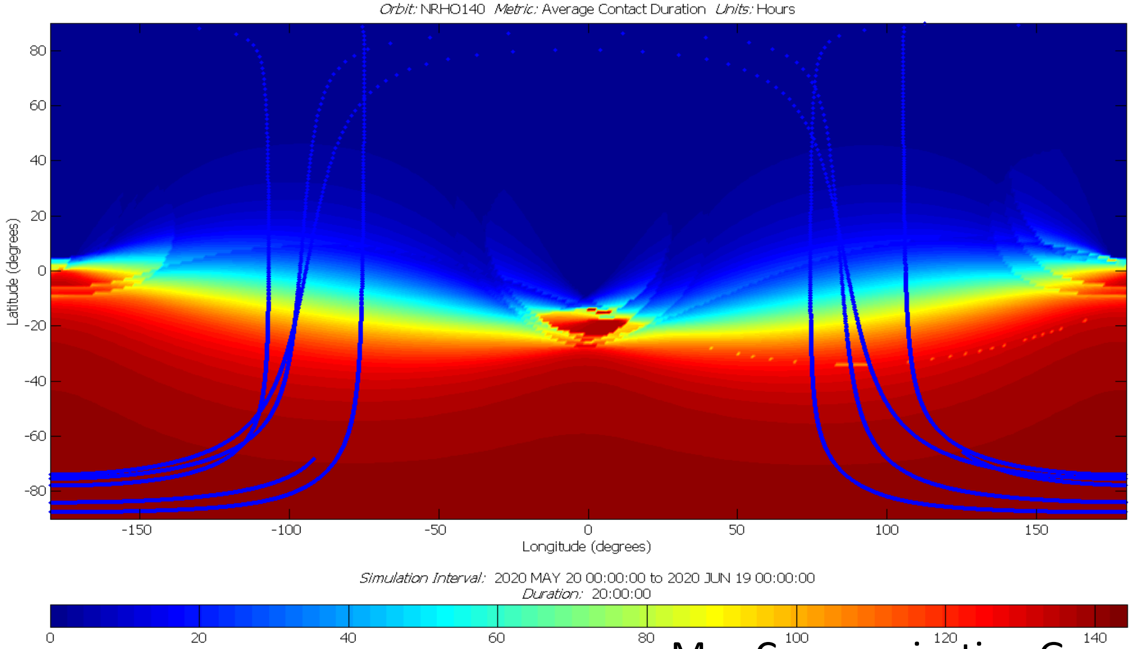
- R. Whitley and R. Martinez, "Options for Staging Orbits in Cislunar Space," IEEE Aerospace 2015 , Mar. 2015.
- Coverage graphics provided by Kar-Ming Cheung and Charles Lee using TOAST.

Lunar Orbital Platform – Gateway (LOP-G): NRHO Trajectory

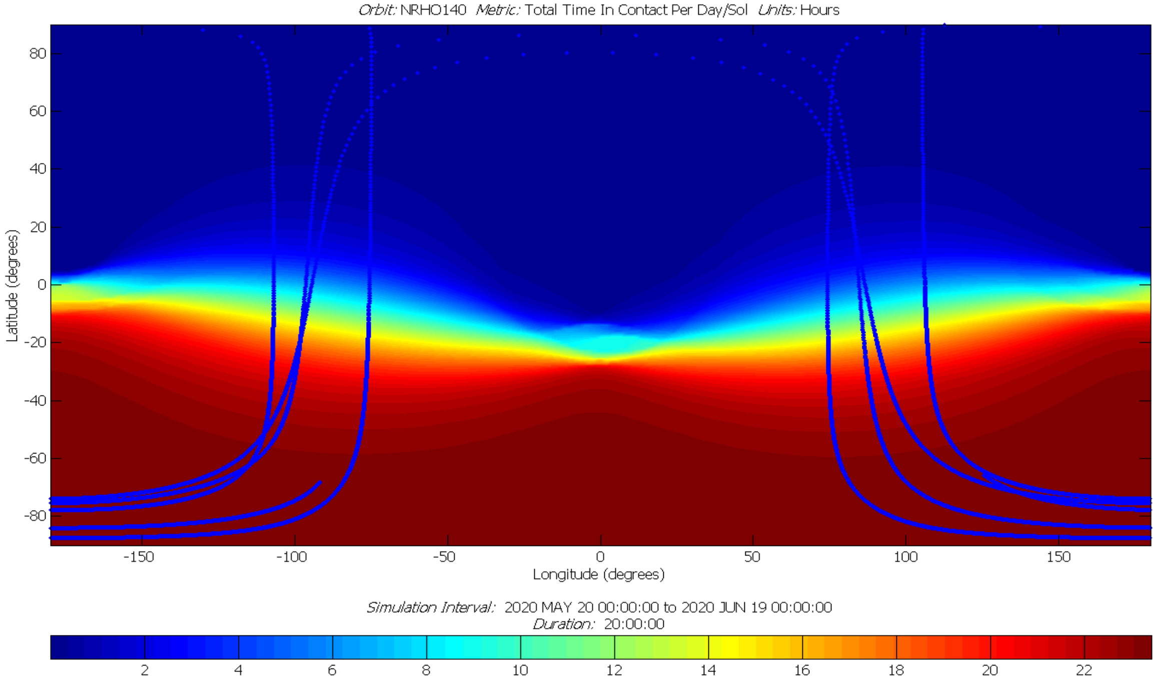
Number of Contacts Per Day



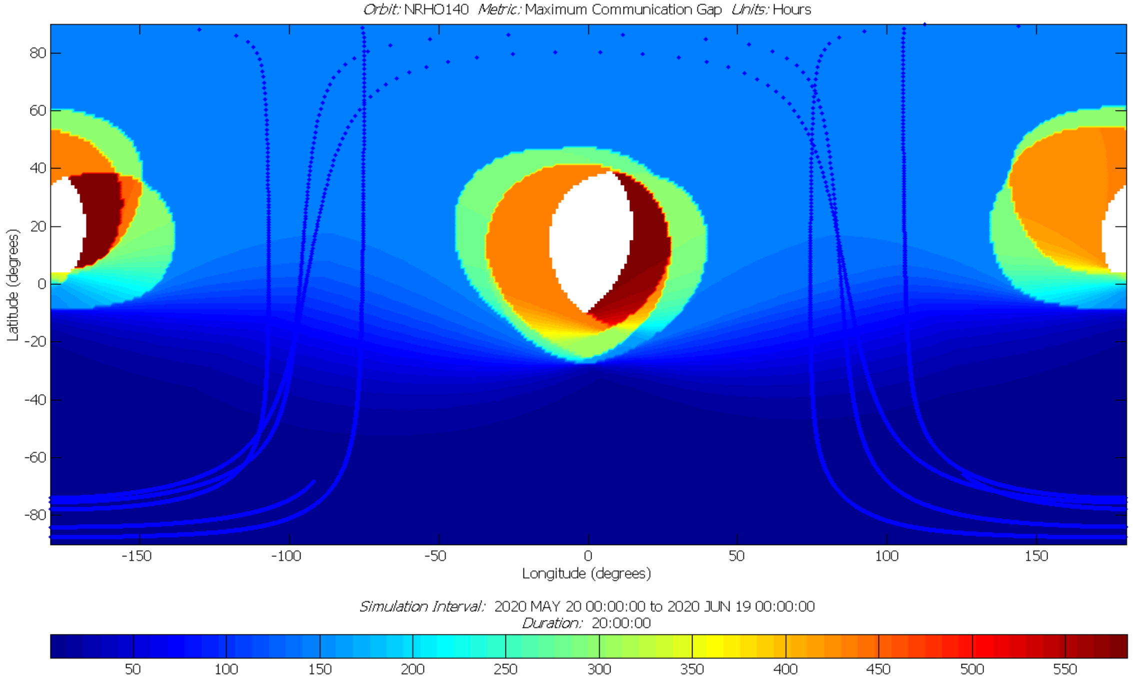
Average Contact Duration



Total Contact Time Per Day



Max Communication Gap

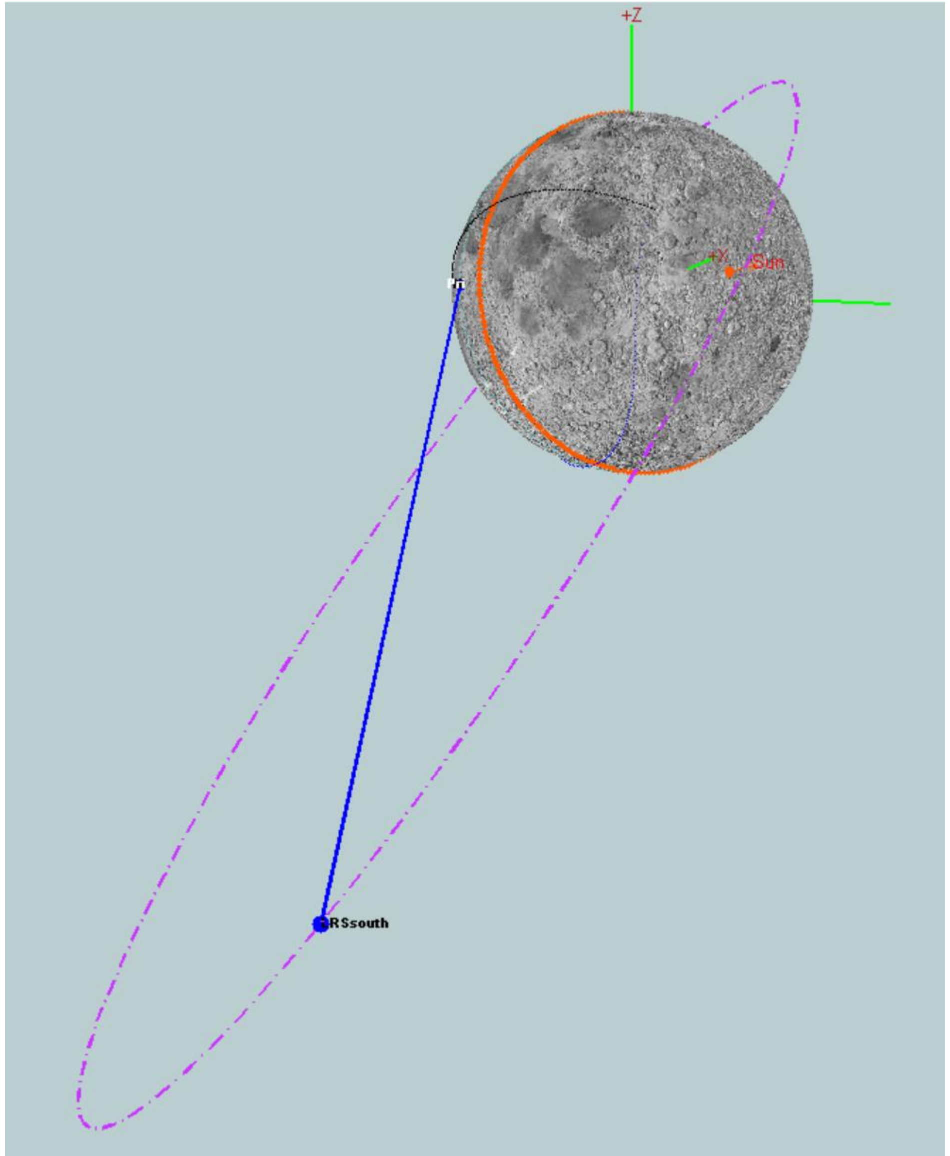


Lunar Communications Pathfinder - Todd Ely Orbit, 12-hour Frozen Orbit

- SMA = 6142.4 km
- Eccentricity = 0.59999
- Inclination = 57.7 deg
- Perilune = 90 deg
- Sim. Time = 27.5 days

- Elliptical polar 500 x 9,900 Km orbit.
- Max velocity 0.68 Km/s.

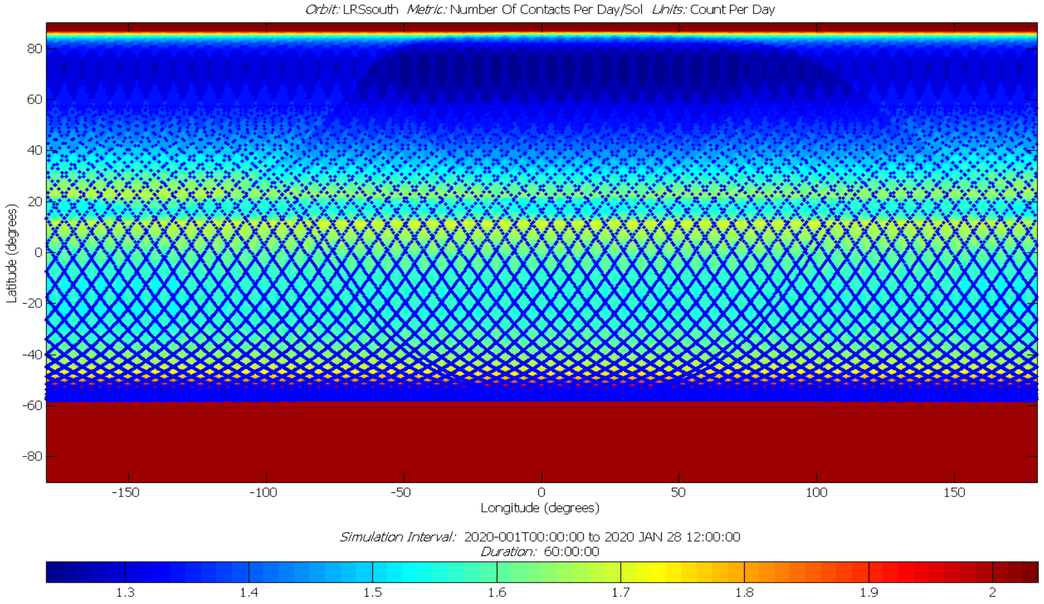
- Max range from S. Pole: ~9,900 Km.
- Continuous coverage of S.Pole for 9.13 hours with a gap of 2.87 hours.



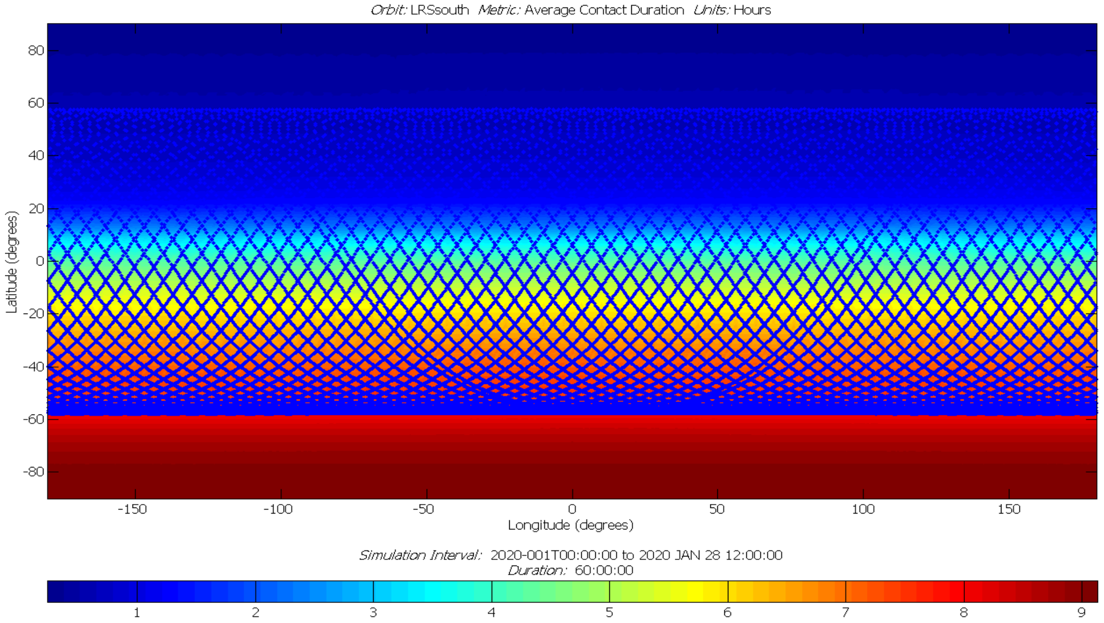
- T. Ely, “Stable Constellations of Frozen Elliptical Inclined Lunar Orbits,” the Journal of the Astronautical Sciences, Vol. 53, No. 3, July – September 2005.
- Coverage graphics provided by Kar-Ming Cheung and Charles Lee using TOAST.

Lunar Communications Pathfinder - Todd Ely Orbit, 12-hour Frozen Orbit

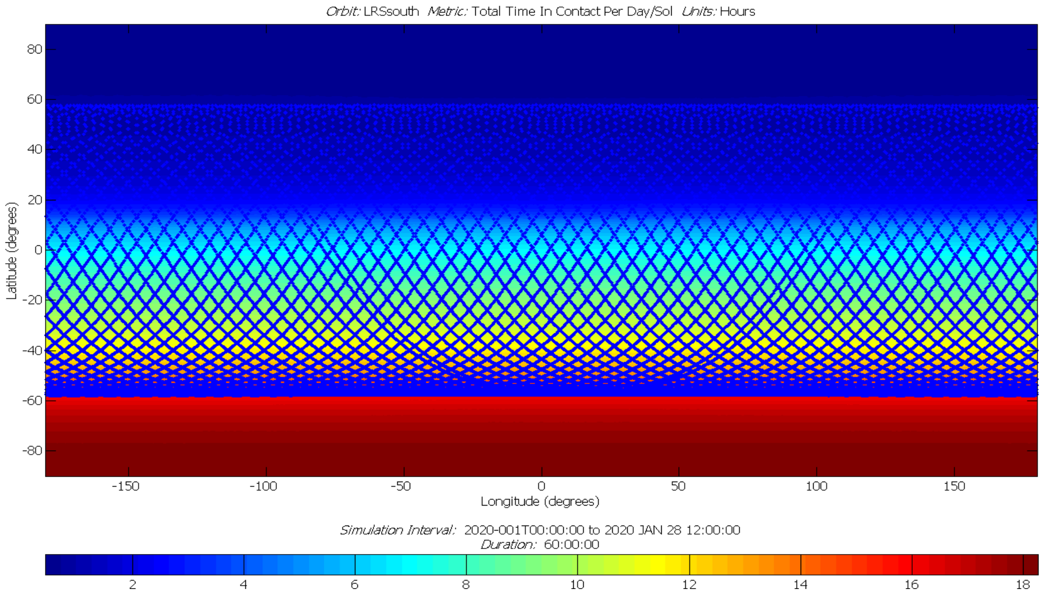
Number of Contacts Per Day



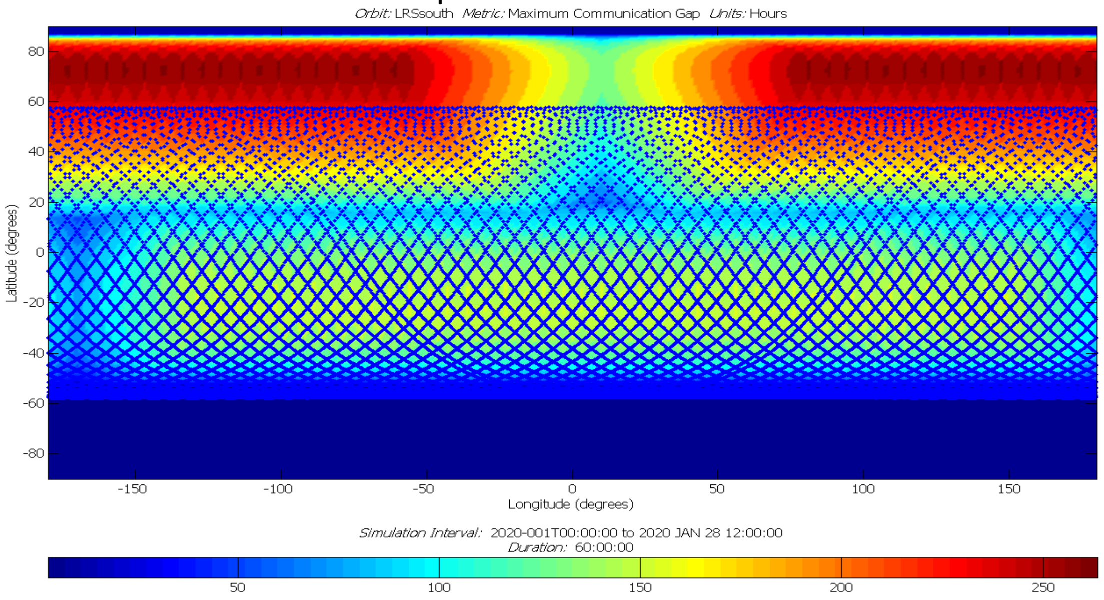
Average Contact Duration



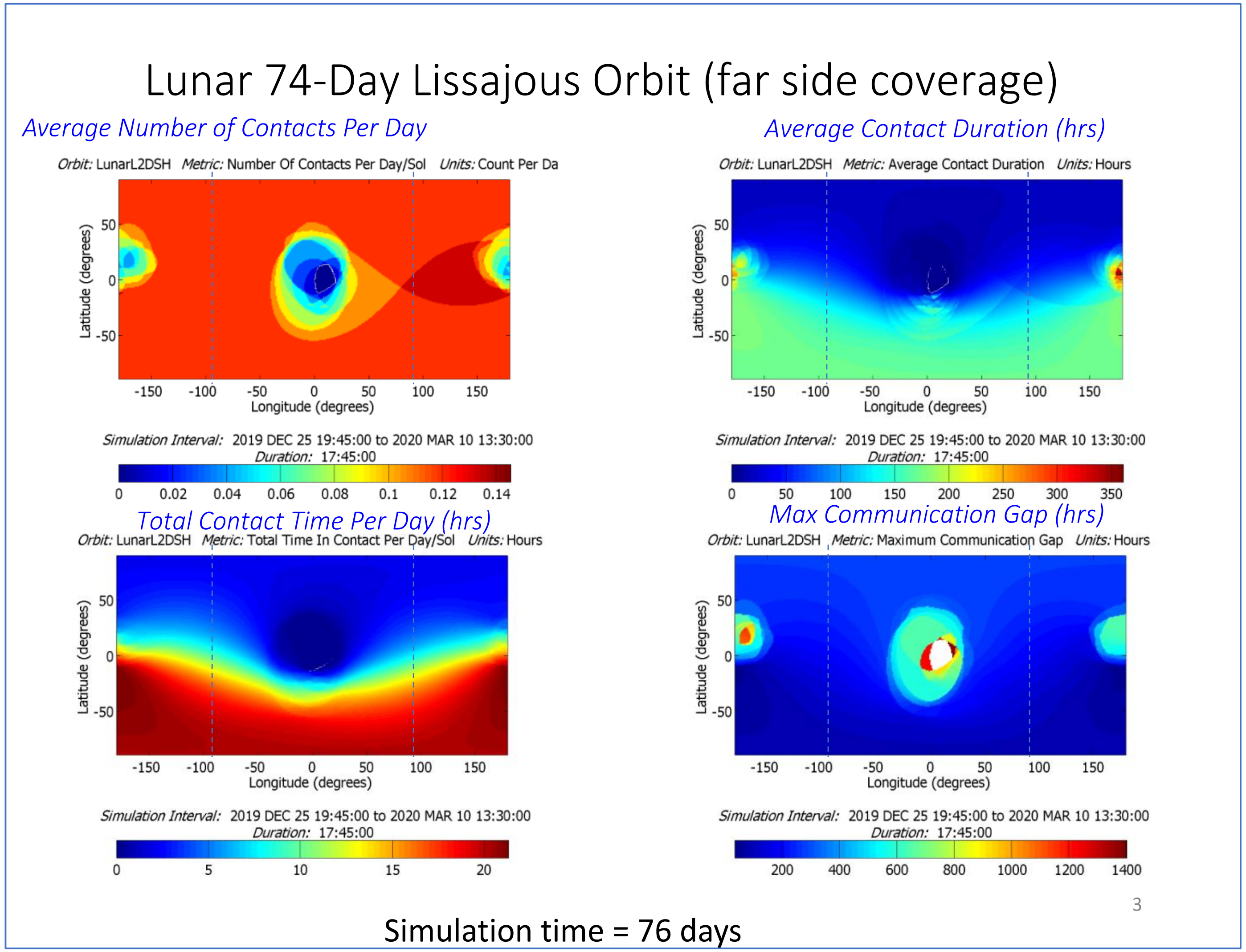
Total Contact Time Per Day

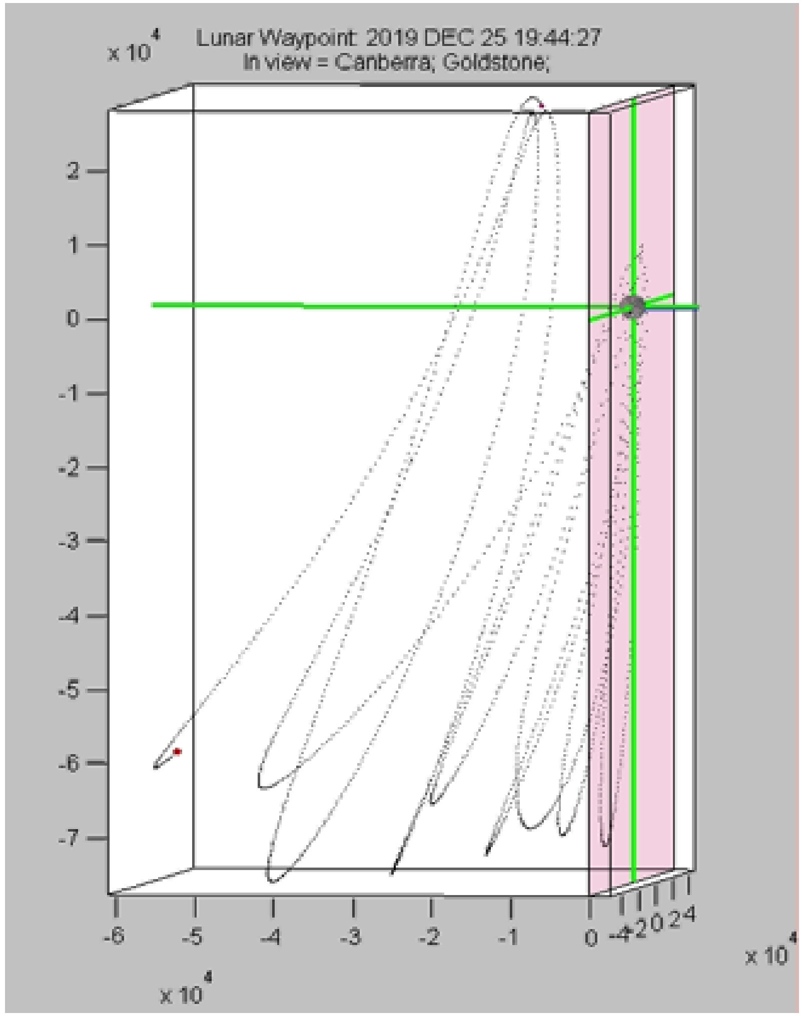


Max Communication Gap



Chang’e-4 Queqiao - 74-Day Lissajous Orbit (1)





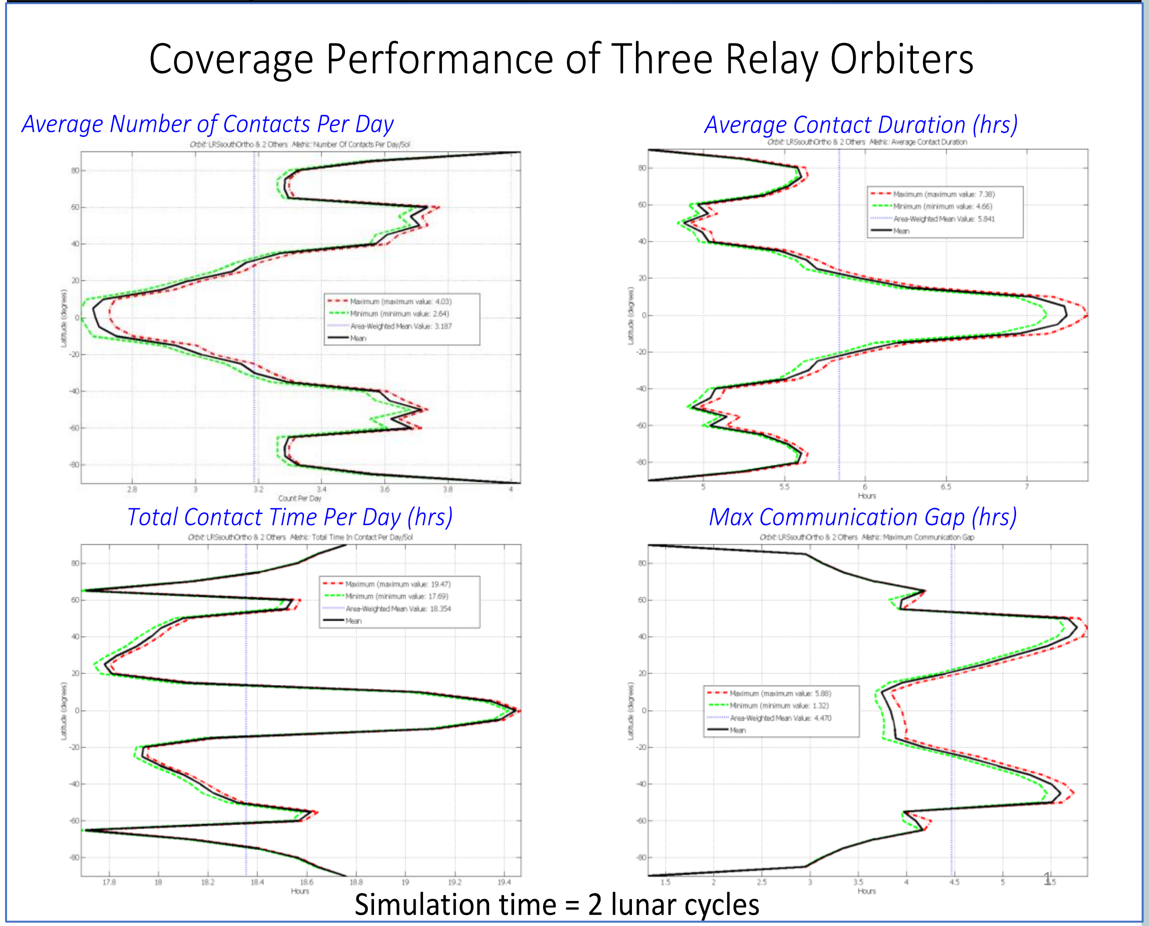
- Kar-Ming Cheung and Charles Lee, “Lunar Relay Coverage Analysis for RF and Optical Links,” AIAA SpaceOps 2018 Conference, 31 May 2018
- Coverage graphics provided by Kar-Ming Cheung and Charles Lee using TOAST.

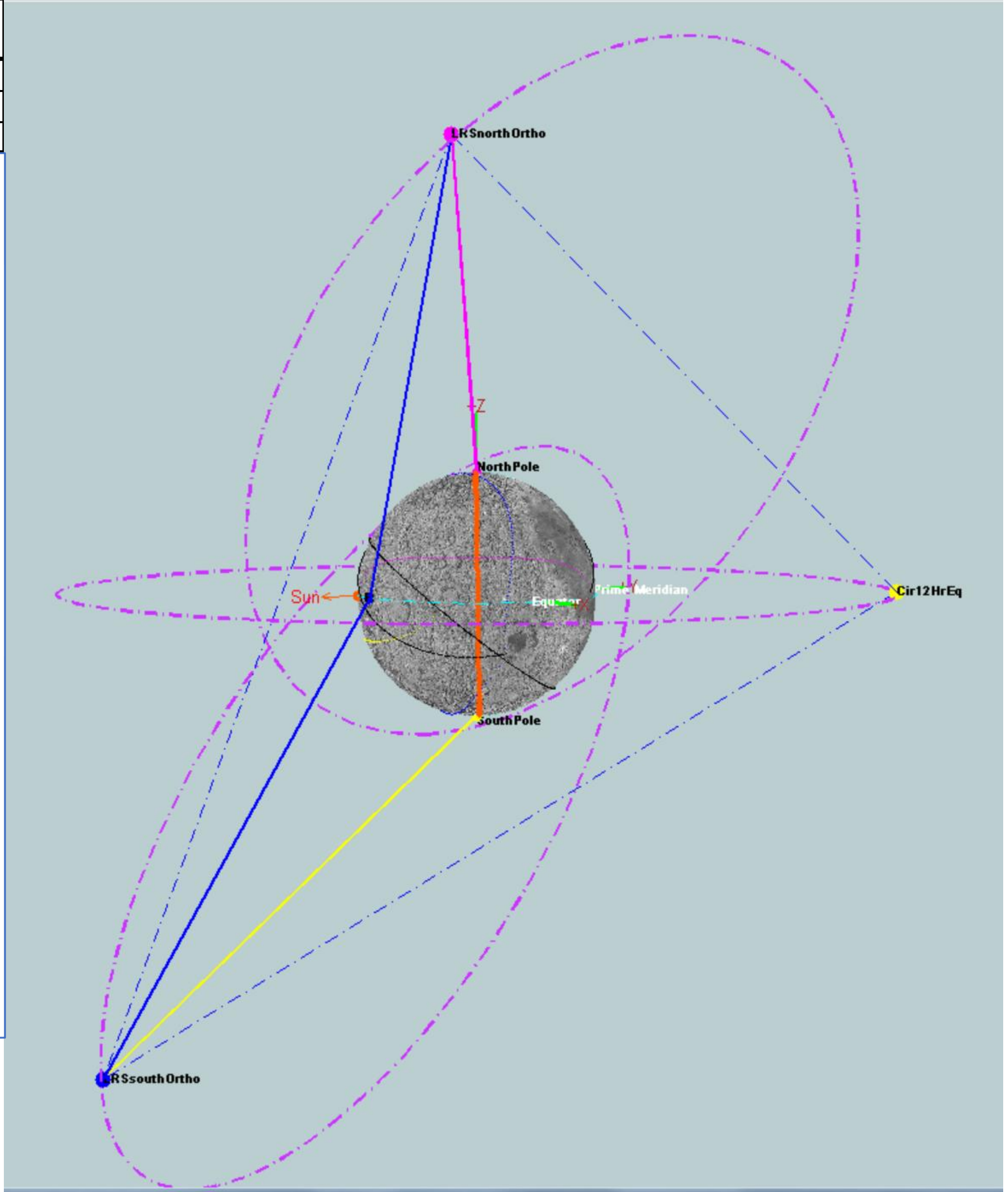
Chang’e-4 Queqiao - 74-Day Lissajous Orbit (2)

- 74-day Lissajous orbit at Earth-Moon L2 (9 loops)
- Covers most of lunar far-side, except the far-side equator
- Favors the far side S. Pole
- 0.8 – 1.2 contacts per 10 days
- During the 74-day orbital period, 9 contacts available at S. Pole.
- Average contact duration at S. Pole is 170 hours.
- Average Communication gaps at S. Pole is 31 hours.
- Range can be as long as 90,000 km
- S. Pole has no or low visibility with Earth, and has to rely on relay orbiter
- An additional ground station in S. Hemisphere (e.g. Heetebeesthoek, S. Africa) helps to eliminate the daily short gaps

The Ideal Lunar Relay Constellation: 2 Polar Frozen, 1 Equatorial Circular (1)

Lunar Satellite Orbits	semi-major axis (km)	Eccentricity	Inclination (deg)	Ascending node (deg)	Argument of Perilune (deg)	Mean Anomaly (deg)
12-Hr Circular Equatorial	6142.4	0	0	0	315	0
12-Hr Elliptical North	6142.4	0.59999	57.7	270	270	0
12-Hr Elliptical South	6142.4	0.59999	57.7	0	90	0





- Kar-Ming Cheung and Charles Lee, "Lunar Relay Coverage Analysis for RF and Optical Links," AIAA SpaceOps 2018 Conference, 31 May 2018
- Wallace Tai, InKyu Kim, SangMan Moon, Day Young Kim, Kar-Ming Cheung, "The Lunar Space Communications Architecture From The KARI-NASA Joint Study," AIAA SpaceOps 2018 Conference, 6 May 2018

The Ideal Lunar Relay Constellation: 2 Polar Frozen, 1 Equatorial Circular (2)

- A few previous studies suggested an "ideal" constellation of 3 orbiters:
  - One in a 12-hour circular elliptical orbit around the equator, and
  - Two in the 12-hour frozen elliptical orbits with their lines of apsides liberating over the North Pole and South Pole respectively.
- Pros
  - Can be built up incrementally – S. Pole, Equator, N. Pole
  - Offer good and relatively even coverage at different latitude
    - Long contact duration (5 – 7 hours)
    - Large total contact time per day (17.6 – 19.4 hours)
    - Short gap time (1.4 – 5.8 hours)
- Cons
  - Requires launching three satellites into orbit